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Color Space of the Coloroid Color System

The Coloroid color system is a Hungarian standard color order system. This article describes the color space of the Coloroid system and its relationship to the CIE colorimetric space and the spaces associated with the Munsell and DIN color order systems. The Coloroid system is presented as, a compromise of principles of uniformity in regard to color difference and color harmony, as well as ease of mapping into the CIE colorimetric space.

Introduction

The Coloroid system was developed at the Technical University, Budapest, Hungary, for use in environmental color design. Finalization of the system relied on tests of the psychometric scales of the color system, made since 1962 under the guidance of the author, involving tens of thousands of test subjects. The overall results of these tests and the system itself were presented[1] earlier in this journal.* This article presents a description of the color space associated with the Coloroid system.

The advantages and disadvantages of the color space implied by a color system emerge in practical use. New ideas are more easily adopted if they have their roots in established ideas. Therefore, after an introduction, the color space associated with the Coloroid color system is presented on the basis of experience gained from use of the color sample collections that embody the Coloroid, the DIN, and the Munsell color systems.[2–4]

The Coloroid System as a Compromise

The Coloroid color space represents a compromise between two objectives. First, achieving perceptual uniformity of color space was attempted. The concept of a perceptually uniform color space may be given two interpretations.[5,6] Either uniformity depends on the color-difference-perception ability of the human visual system, or uniformity relies on the ability of appreciation. In the first case, perception-threshold measurements are applied to define color-space scales, such as in the Munsell Renotation system. In the second case, color-space scales rely on harmony-threshold measurements. In these tests the minimum difference between two colors in a given color composition is to be determined such that the two colors can not only be perceptually distinguished but also aesthetically appreciated in the composition.[7,8] This minimum difference between two colors I call the harmony threshold. Colors in a composition differing by less than the harmony threshold are considered fraternal rather than independent colors. A series of colors spaced at harmony thresholds having a beginning and an end is, when viewed as a whole, seen to be perfectly uniform. This uniformity based on harmony-threshold measurements is called aesthetic uniformity. To create a color space according to the latter interpretation of perceptual uniformity has been attempted in the Coloroid system. The size of the unit of harmony difference has been found to vary in terms of units of perceptual difference across color space.[9,10]

Second, a simple mapping of the experimental idealized color-perception space into the color-excitation space of the CIE colorimetric system was endeavored.[1,11,12]

This dual goal has resulted in the color space of the Coloroid color system, which approximates aesthetic uniformity fairly well with an unambiguous mapping into the CIE system.

The Coloroid color space is embedded in an orthogonal circular cylinder (Fig. 1*), with the achromatic colors on

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*Following are corrections for two errors found on page 120 of ref. 1: Equation (19) reads correctly:

$$T_{\varphi} = 100 \frac{Y(x_0\varepsilon_w - x\varepsilon_w)}{100(x\varepsilon_\lambda - \varepsilon_\lambda x_\lambda) + Y_\lambda(x_0\varepsilon_w - x\varepsilon_w)}$$

Equation (22) reads correctly:

$$y = \frac{V^2 + 100T\varepsilon_\lambda y_\lambda - TY_\lambda}{\varepsilon_w(V^2 - TY_\lambda) + 100\,T\varepsilon_\lambda}$$

*Symbols used in Fig. 1 are defined in Table I.

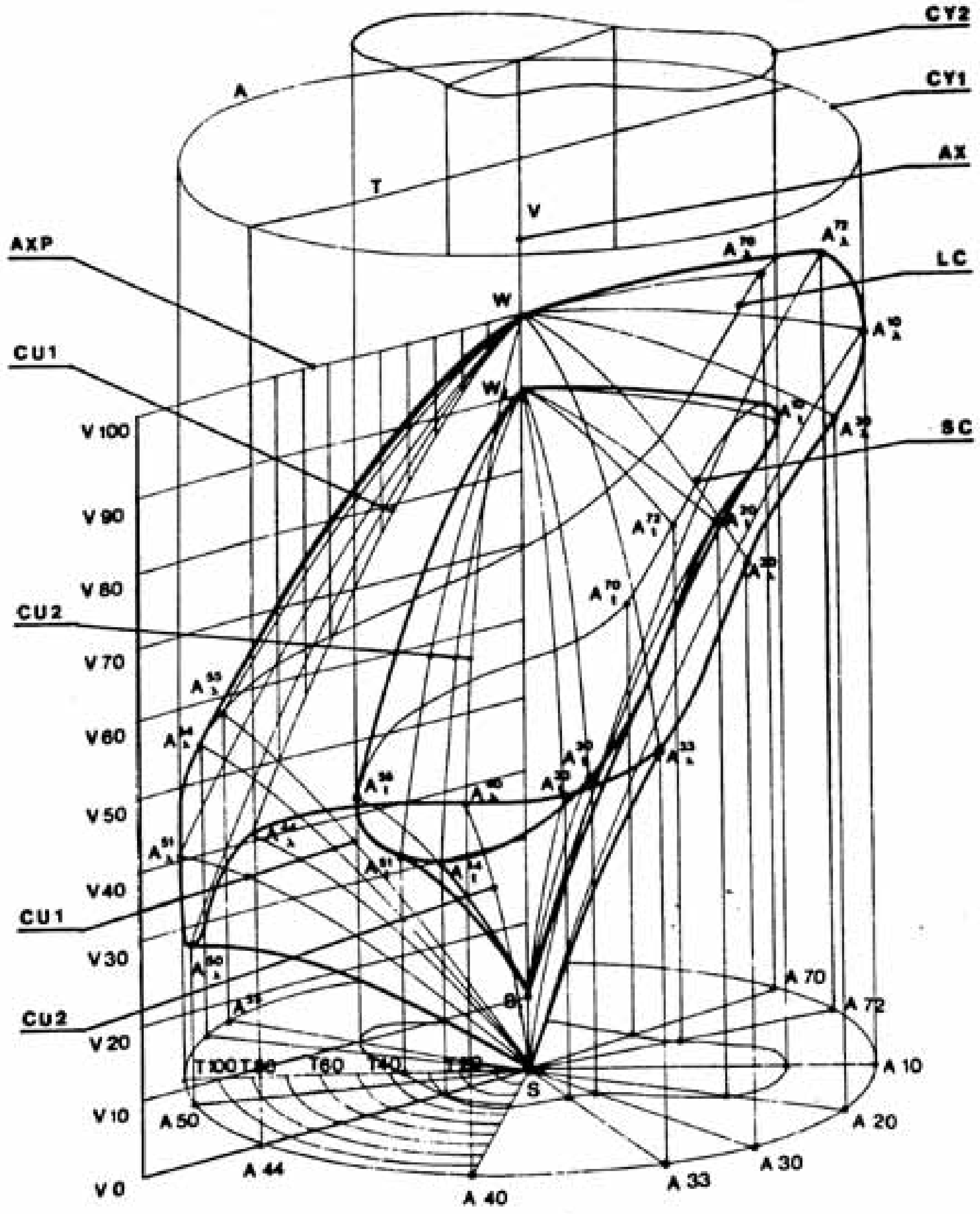

FIG. 1. View of the spatial model of the Coloroid color system (for legend, see Table I).

its axis. The axis begins with absolute white and ends with absolute black. These are, respectively, the colors of a perfectly diffuse reflecting surface irradiated by CIE illuminant C, and of a perfect light-absorbing surface, that is,

$$Y_w = 100 \text{ and } Y_s = 0$$

where Y_w and Y_s are CIE tristimulus values of absolute white and of absolute black. The color coordinates of absolute white and absolute black of the Coloroid color system are identical with the color coordinates of CIE illuminant C in the CIE 1931 chromaticity diagram.

The Coloroid limit colors, spectrum colors from $\lambda = 450$ nm to $\lambda = 625$ nm of the spectrum locus in the CIE 1931 chromaticity diagram and purple colors on the straight line connecting these points, are located on a curve traced on the shell of the cylinder. The tristimulus values X_λ, Y_λ, Z_λ of Coloroid limit colors are 100 times the color matching functions $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$ at dominant wavelength λ_d with a bandwidth of the equal-energy spectrum of 1 nm, that is,

$$X_\lambda = 100\,\bar{x}_\lambda;\ Y_\lambda = 100\,\bar{y}_\lambda;\ Z_\lambda = 100\,\bar{z}_\lambda.$$

Distances between points on the curve in Fig. 1 and the normal plane at point S of the achromatic axis are directly proportional to the tristimulus value Y of the given color. Among the limit colors, 48 aesthetically equidistant colors have been assigned integer numbers, e.g., $A10$, and termed Coloroid basic colors. Colors of the same hue are located on axial sections, those of the same luminosity on planes normal to the axis, and those of the same saturation on coaxial cylindrical surfaces. The Coloroid color space accommodates the Coloroid color solid comprising all realizable surface colors. The Coloroid color solid includes the colors of the realized color collection.[13]

CIE tristimulus values at each point of the Coloroid color space can be expressed as the sum of the products of CIE tristimulus values of the Coloroid limit color and the respective Coloroid tristimulus values of absolute white and absolute black (Fig. 2, Table I). Any surface color in the Coloroid color solid may also be expressed as an additive mixture of a surface color of the same dominant wavelength but more saturated, of a brighter, and of a darker achromatic surface color[14] (see also Fig. 2 and Table I). In Fig. 2 a part bounded by axial sections containing hues $A20$ and $A44$ of the spatial model of the Coloroid color system has been removed. On both axial sections, positions of the two most saturated surface colors A20, and A44, corresponding to the hues of the axial sections, have been marked. Again, boundary curves joining these points, containing surface colors in these axial sections, have been traced. Horizontal lines of the mesh on the Coloroid half plane of hue $A44$ accomodate colors of the same lightness, and vertical ones those of the same saturation. Accordingly:

$$X = pX_\lambda + wX_w + sX_s \quad X = p_tX_{t\lambda} + w_tX_{tw} + s_tX_{ts}$$

$$Y = pY_\lambda + wY_w + sY_s \quad Y = p_tY_{t\lambda} + w_tY_{tw} + s_tY_{ts}$$

$$Z = pZ_\lambda + wZ_w + sZ_s \quad Z = p_tZ_{t\lambda} + w_tZ_{tw} + s_tZ_{ts}$$

(see Table I for definitions).

Scaling in the Coloroid Color Space

Next, the scaling of Coloroid hue, Coloroid saturation, and Coloroid lightness in the Coloroid color space are considered, first from the viewpint of aesthetic uniformity, and then from that of a simple mapping into the CIE system.

Hue Scales in the Coloroid Color Space

According to the concept of aesthetic uniformity, equal hue steps rely on the uniformity of harmony intervals throughout the color space. The result should be a compromise between uniformity and color abundances in the color ranges utilized in environmental color design. In a constructed environment, only colors that can be appreciated aesthetically in a composition or in a spatial complex should be used. Since, according to our tests,[15] the largest deviations between perceptual scales and scales of harmony occur in the green and purple color ranges, these are likely to be the areas where color scales of the Munsell and DIN systems, which are based on perceptual scaling, differ most from those of the Coloroid systems, which are based on harmony scaling.

For the purpose of comparison, color samples have been classified into five groups according to dominant wavelength. Yellow, red, purple, blue, and green ranges have been assigned colors of dominant wavelengths, respectively, from 567 to 590 nm, 591 to 625 and −491 to −500 nm, −501 to −570 nm, 449 to 495 nm, and 496 to 566 nm. Distribution of color samples for these ranges as a percentage of the total sample assortment for the Coloroid, the Munsell, and the DIN systems is seen in Table II.

The sample percentages for the Coloroid color collection in the yellow, red, and blue ranges are seen to be intermediary to those of the other two color systems, whereas the Coloroid system contains proportionally fewer purple and more green samples than either of the other two systems. We are of the view that the requirements of design practice, affected by fashion trends, tend to favor the Coloroid recommendations.

The aspect of simple correlation with the CIE colorimetric system suggests a relationship of hue to dominant wavelength. In the Coloroid system, colors of the same hue are assigned the same dominant wavelength. This is not so in the Munsell system, making the relationship of its hue scales to the CIE system much more complicated.

Hue spacings of the Coloroid and the Munsell systems have been compared in Fig. 3. The systems have been centered at the location of illuminant C on the CIE 1931 diagram. The 48 Coloroid basic colors corresponding to the 48 basic hues are identified on the outer circle. Their numbering ranges from 10 to 76, with certain numbers left out. Intersections of radii crossing the points with the spectrum locus define the dominant wavelengths of the Coloroid hues. These dominant wavelengths were tabulated in ref. 1. Circular arcs of different lengths indicate forty Munsell hues in the inner circle. The circular arc lengths depend on the wavelength ranges needed to characterize the indicated colors

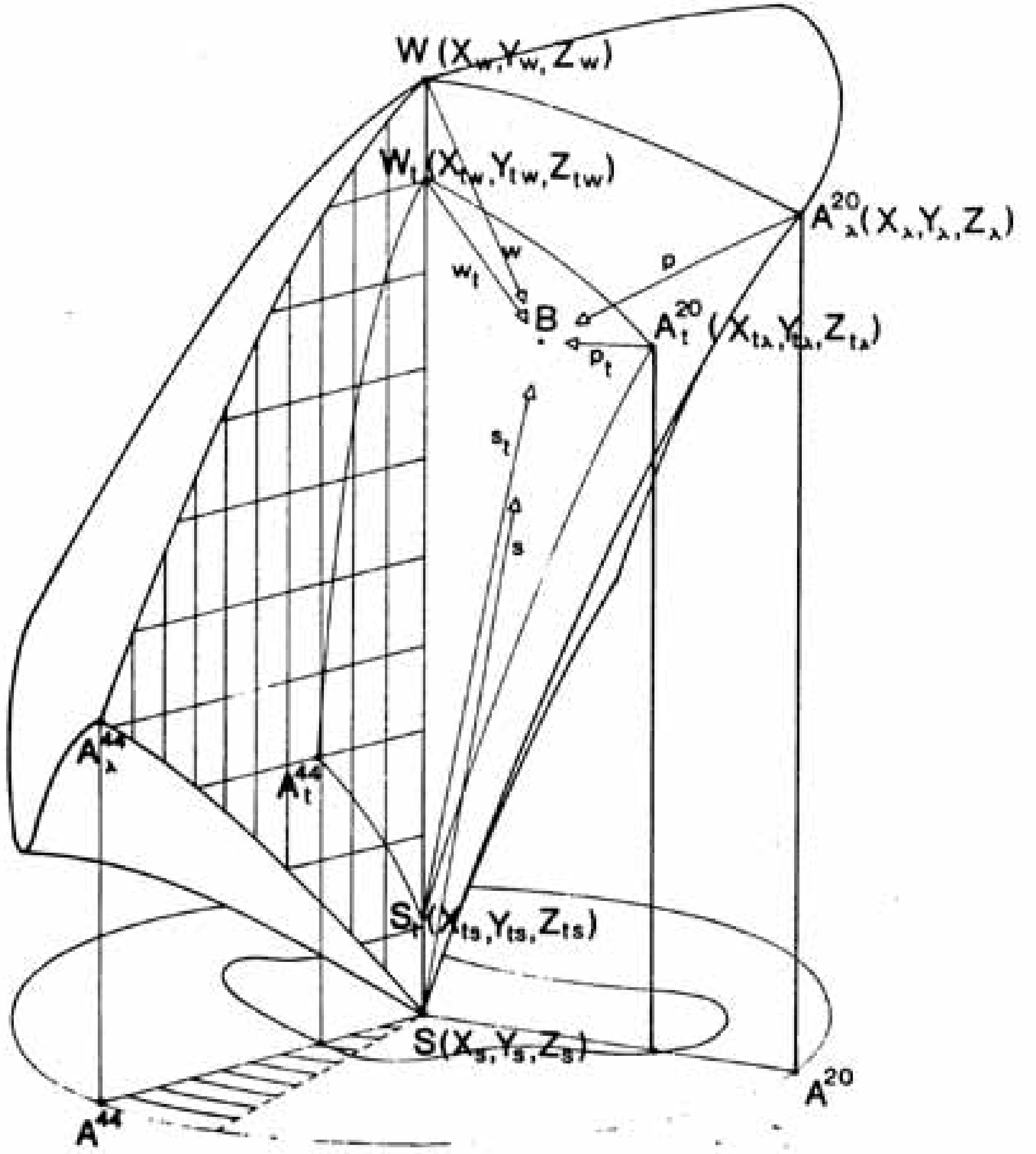

FIG. 2. Derivation of the Coloroid colors from tristimulus values of the CIE colorimetric system. Additive mixing of surface colors. See text for details (for legend see Table I).

of a given hue but varying in saturation in the Munsell system. In this system as many as four different hues may have the same dominant wavelength, depending on saturation. The figure seems to indicate that the ability of the human visual system to distinguish hues is more differentiated in the ranges of bluish-green and purple than, e.g., in the yellow range. This impression is validated not only by our experiments but also by practical experience of people working with colors.[16]

In Fig. 4, Munsell 5.0 YR and Coloroid 22, colors of the same hue, are defined according to dominant wavelengths. Plane *C* contains all the colors of the Coloroid axial section. Colors of the Munsell axial section are in planes of different dominant wavelength, parallel to plane *C*. Munsell saturations lie on the horizontal axis, and Munsell and Coloroid lightnesses on the vertical axis of plane *C* of the view presented. Numerical values of Munsell and Coloroid lightnesses are on the right and on the left side of the diagram, respectively. Identical Coloroid saturations are located on curves in plane *C* (T10 to T50). Plane *C* contains all the colors of the Coloroid axial section. Colors of the Munsell axial section form surface *M*. Dominant wavelengths of colors represented by surface points and distances of the given points from plane *C* are directly proportional.

TABLE I. Definitions of symbols and abbreviations used in the text and figures.

Symbol	Definition
Figure 1	
CY1	Circular directrix of the orthogonal cylinder comprising the Coloroid color solid
CY2	Irregular directrix of the orthogonal cylinder comprising the Coloroid color solid (surface colors)
AX	Achromatic axis of the Coloroid color system
LC	Spectrum locus of the Coloroid space on the shell of the orthogonal circular cylinder comprising the Coloroid color space
SC	Locus of the most saturated surface colors of the Coloroid color space on the shell of the cylinder of irregular directrix *CY2*
AXP	Axial section of the Coloroid color space; planes crossing the achromatic axis cut out so-called Coloroid half planes
CU1	Boundary curves bounding colors in the Coloroid half planes
CU2	Boundary curves bounding surface colors in the Coloroid half planes
W	Absolute white of the Coloroid color system, top of the achromatic axis
W_t	Location of the lightest achromatic surface color on the achromatic axis
S	Absolute black of the Coloroid color system, bottom of the achromatic axis
S_t	Place of the darkest achromatic surface color on the achromatic axis
A	Symbol of Coloroid hue. Coloroid includes 48 basic hues marked by omitting certain numbers from the range 10 to 76. A hue is designated by the letter *A* followed by the hue number. For example, *A10* refers to colors with dominant wavelength 570.83 nm. Colors of the same hue form axial sections.
A_λ	Symbol of Coloroid limit color. In the Coloroid system, there are 48 basic colors between limit colors, marked like the basic hues.
A_t	Symbol of the most saturated Coloroid surface colors for each hue, marked like the basic hues.
T	Symbol of Coloroid saturation. Coloroid saturation increases linearly along each normal to the achromatic axis, from the axis towards the shell of the cylinder comprising the Coloroid limit colors. The numerical value of saturation is zero at the achromatic axis and 100 at the cylinder shell. Colors of the same saturation form coaxial cylindrical surfaces.
V	Symbol of Coloroid lightness. Coloroid lightness increases linearly from the plane normal to the achromatic axis at the absolute black point to the normal plane at the absolute white point. The numerical value of lightness is zero in the plane at the absolute black point and 100 in the plane at the absolute white point. Colors of equal lightness form parallel planes normal to the achromatic axis.
Figure 2	
B	An arbitrary color in the Coloroid half plane of basic hue *A20*.
X_w, Y_w, Z_w	CIE tristimulus values of Coloroid absolute white.
X_s, Y_s, Z_s	CIE tristimulus values of Coloroid absolute black.
$A20_\lambda$	Coloroid limit color defining the hue of Coloroid half plane *A20* containing color *B*.
$X_\lambda, Y_\lambda, Z_\lambda$	Tristimulus values of Coloroid limit color *A20*.
p	Coloroid color content (excitation purity). Coloroid tristimulus value. If color *B* is to be expressed as an additive mixture of $A20_\lambda$, *W*, and *S*, then *p* is the percentage of $A20_\lambda$ in the mixture.
w	Coloroid white. Coloroid tristimulus value. If color *B* is to be expressed as an additive mixture of $A20\lambda$, *W*, and *S*, then *w* is the percentage of *W* in the mixture.
s	Coloroid black. Coloroid tristimulus value. If color *B* is to be expressed as an additive mixture of $A20_\lambda$, *W*, and *S*, then *s* is the percentage of *S* in the mixture.
W_t	Achromatic surface color brighter than *B*, practically available to produce color *B* by additive mixing.
X_{tw}, Y_{tw}, Z_{tw}	CIE tristimulus values of achromatic surface color W_t.
S_t	Achromatic surface color darker than *B*, practically available to produce color *B* by additive mixing.
X_{ts}, Y_{ts}, Z_{ts}	CIE tristimulus values of achromatic surface color S_t.
$A20_t$	Chromatic surface color in hue plane *A20*, more saturated than *B*, practically available to produce *B* by additive mixing.
$X_{t\lambda}, Y_{t\lambda}, Z_{t\lambda}$	CIE tristimulus values of the chromatic surface color $A20_t$.
p_t	Coloroid tristimulus value of practical color mixing. Percentage of surface color of the same wavelength as, but more saturated than, the surface color to be produced by additive mixing.
w_t	Coloroid tristimulus value of practical color mixing. Percentage of achromatic surface color lighter than the surface color to be produced by mixing.
s_t	Coloroid tristimulus value of practical color mixing. Percentage of achromatic surface color darker than the surface color to be produced by mixing.
X, Y, Z	CIE tristimulus values.

Points for the same dominant wavelengths on surface *M* are connected by curves.

The dominant wavelength of all colors of Coloroid hue 22 in plane *C* of the figure is the same. The dominant wavelengths of colors of Munsell hue 5.0 YR vary. Only the dominant wavelengths of colors along curve *m* are identical to that of Coloroid hue 22; those of the other colors are higher or lower, resulting in the departure of the curved surface from plane *C*. Curiously, differences in dominant wavelength are the greatest in very light and very dark ranges of the least saturated colors, exactly where—according to decades of practical experience with visual colorimeters—the human visual system is the least able to distinguish hues precisely. Test subjects separately viewing any collection of color samples of identical hue of the three color systems were found to perceive all the colors in the collection to have perfectly identical hue. When collections from different systems were directly compared, the judgments regarding the preferred system varied; however, no system was found to be preferred at a statistically significant level.

TABLE II. Percentage of color samples of the Coloroid, Munsell, and DIN color collections falling into five color ranges (see text for definition of ranges).

	Coloroid	Munsell	DIN
Yellow	25	21	30
Red	18	16	21
Purple	15	19	21
Blue	19	23	11
Green	23	21	17

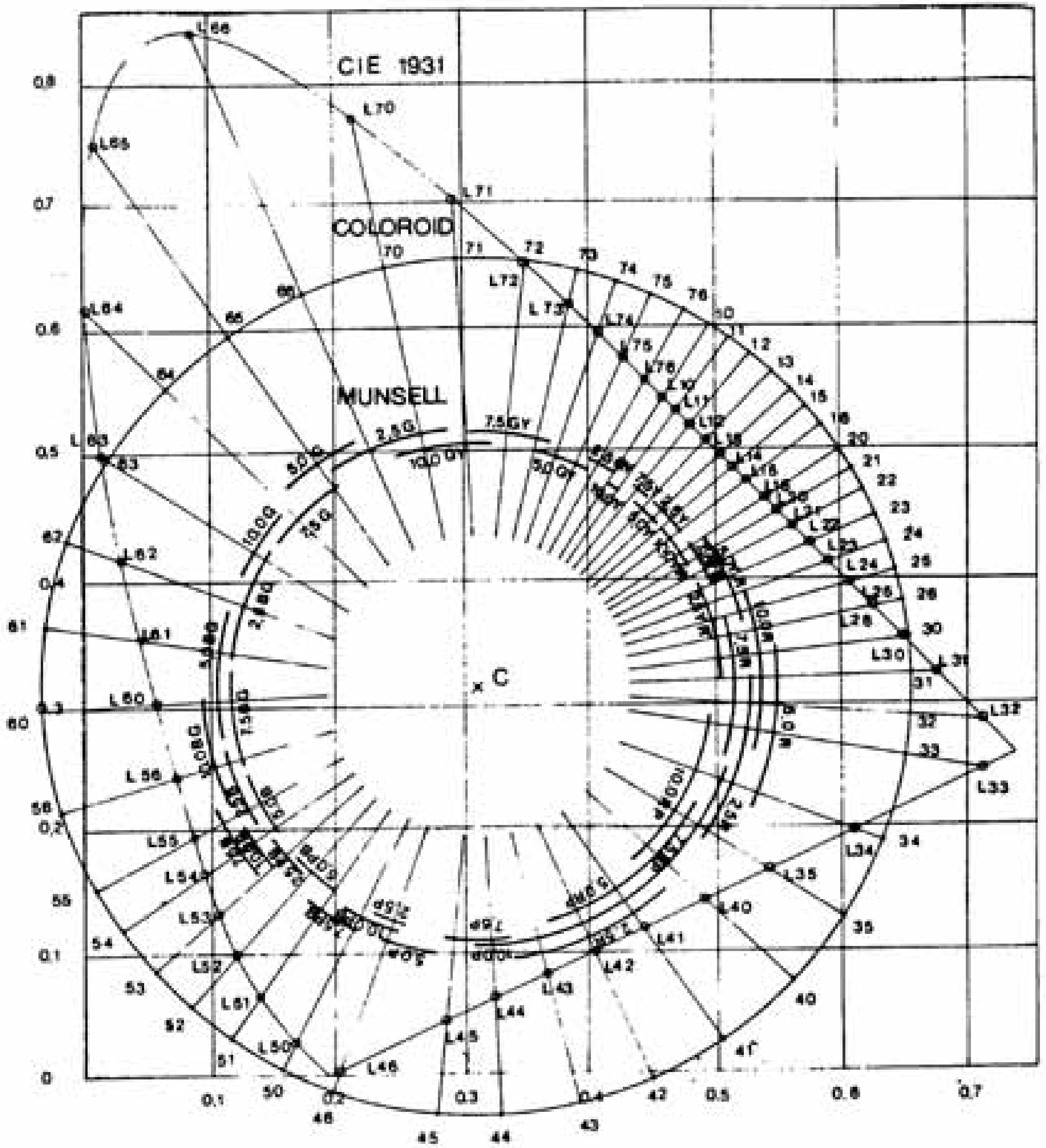

FIG. 3. Positions of dominant wavelengths of colors of the same hue in the Coloroid, Munsell, and DIN color collections superimposed on the CIE 1931 chromaticity diagram.

Lightness Scaling in the Coloroid Color System

According to the concept of aesthetic uniformity, a uniform lightness scale is developed from equal harmonic intervals between absolute white and absolute black. When observers examine juxtaposed grey scales of the Coloroid, Munsell, and DIN systems, that of the Coloroid system is judged to vary evenly, while those of the Munsell and the DIN systems vary more gradually (see Fig. 5) in the darker ranges.[17] These statements are supported by experiments involving thousands of test subjects.[5]

The grid on which the tristimulus values Y are located in Fig. 5 has square-root spacing. The situation is further complicated by the fact that these scales are valid for the complete space or color solid only in the Coloroid and Munsell color systems. Differences in the scale divisions clearly depict deviations between scales relying on harmonic and those relying on perceptual scaling experiments. These deviations are partly responsible for the fact that the Munsell and DIN color sample collections include many more dark shades than does the Coloroid collection. The desirability of a simple mapping into the CIE colorimetric system was

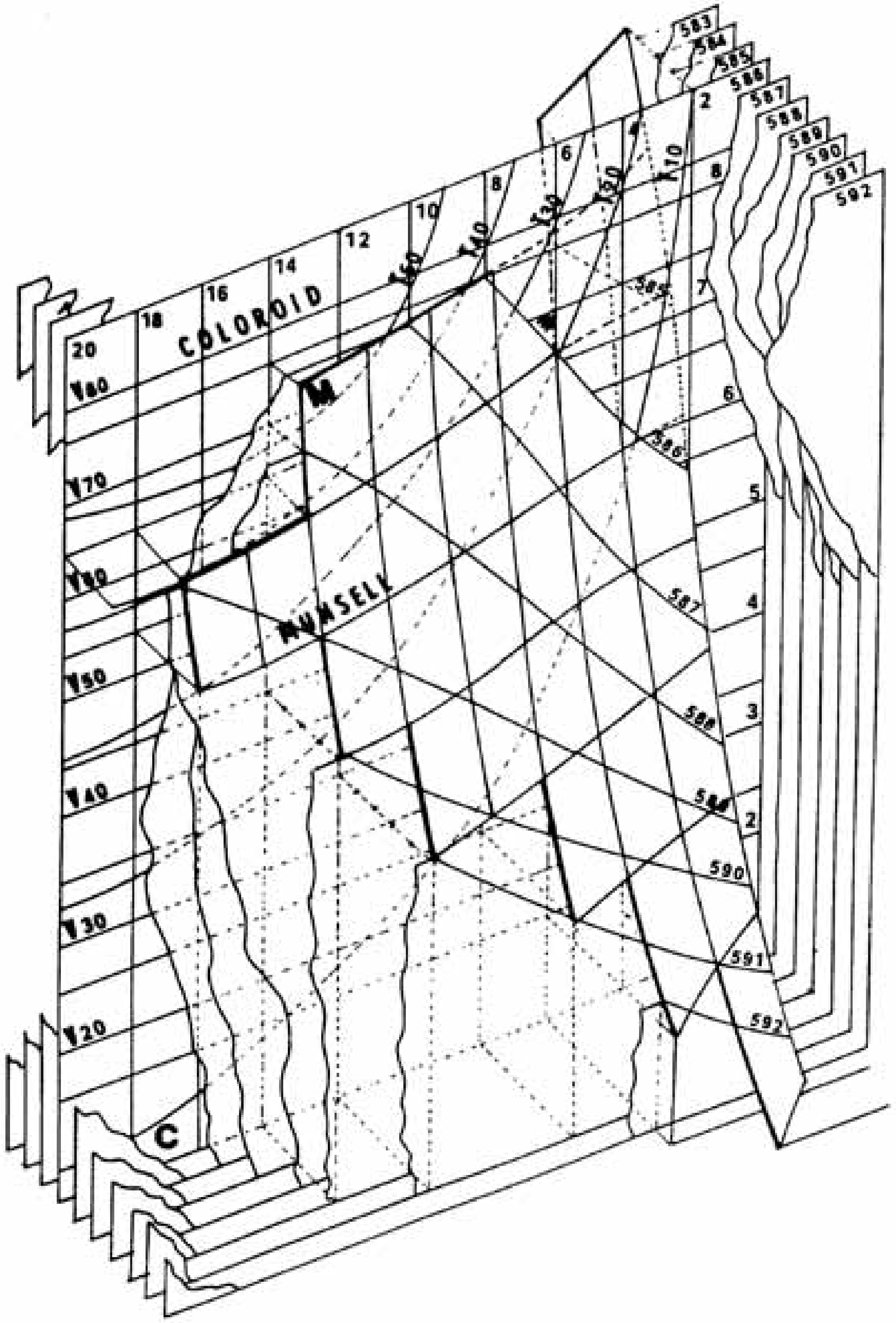

FIG. 4. Dominant wavelengths of colors of different lightnesses and saturations in axial sections of the same orange hue of the Coloroid and the Munsell systems. See text for explanation.

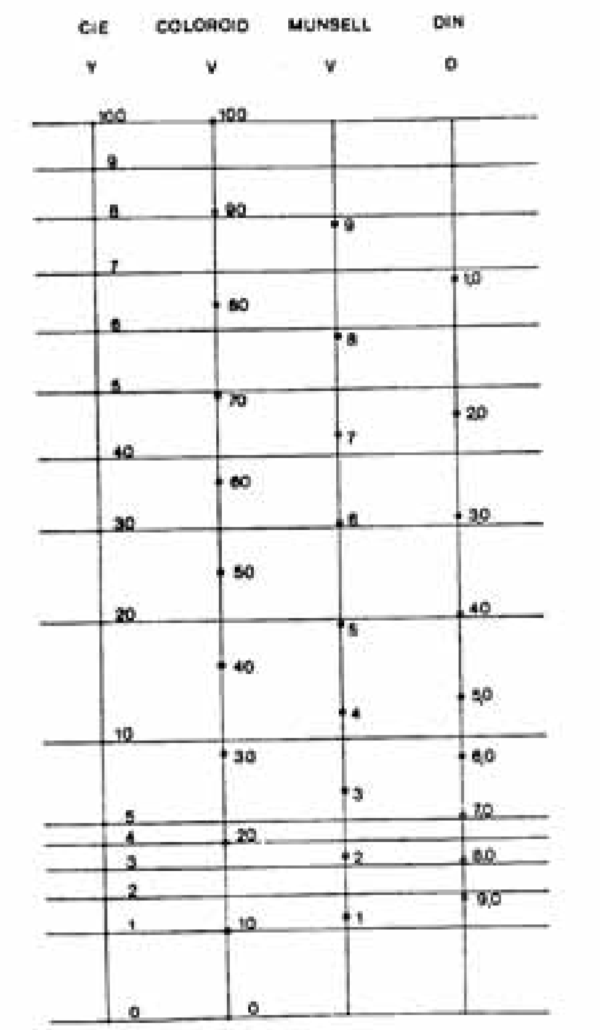

FIG. 5. Lightness scales of the Coloroid, Munsell, and DIN color systems compared to CIE tristimulus value *Y*.

kept in mind in relating CIE tristimulus value *Y* and Coloroid lightness value *V* of a color as:

$$V = 10\,Y^{1/2}$$

This relationship fairly approximates aesthetical uniformity. This statement is similar to that made by the painter Munsell in considering color scales.[18] By definition, Coloroid lightness expresses the distance of the given color from absolute black on an aesthetically uniform scale of 0 to 100. Coloroid lightness of any color is numerically obtained as

$$V = 10\,(pY_\lambda + 100w)^{1/2} \text{ and } V = 10\,(p_sY_{s\lambda} + w_sY_{rw} + s_sY_{rs} -)^{1/2}$$

for symbol definitions see Table I).

Saturation Scaling in the Coloroid Color System

According to the concept of aesthetic uniformity, a uniform scale of saturation relies on equal harmonic intervals from any grey to the most saturated color of the same lightness. In the case of saturation, uniformity of harmonic intervals also assumes overall consideration of the entire color space. As a consequence, dark ranges in the Coloroid system include fewer, and medium and light ranges more, saturation intervals than in the Munsell or DIN color systems.

A simple mapping into the CIE colorimetric system was kept in mind when leaving Coloroid saturation independent of hue and lightness. Each color of the color space can be produced by additively mixing the proper spectrum color—or two spectrum colors in the purple range—with absolute white and absolute black. The quantity *p* of the spectrum color (Coloroid limit color) required to produce a given color is called the color content (excitation purity). In Fig. 6 ten coaxial cylinder surfaces of the color solid have been spaced evenly from grey to the spectrum color, corresponding to the variation of *p* from 0 to 1. In the Coloroid system an aesthetically uniform scale of saturation from zero to 100 expresses the distance of the color from an achromatic color of the same Coloroid lightness, achieved by directly relating Coloroid saturation *T* to *p* as

$$T = pT_\lambda = 100p \text{ and } T = p_sT_{s\lambda}$$

where T_λ is the saturation of the Coloroid limit color and $T_{s\lambda}$ is the saturation of a surface color more saturated but of the same dominant wavelength as that of the surface color in question (other symbol definitions are found in Table I).

Munsell and DIN saturation data are indicated as lines in Fig. 6. Colors of the same Munsell or DIN saturation may have a wide range of color content *p*. The question whether or not variation of saturation should be independent of color content *p* and dependent on variation of hue and lightness may be answered by comparing color sample collections. The human visual system is least able to distinguish variation in saturation. Whether two samples of the same hue are equally or differently saturated and, if differently, what the ratio of their saturations is in terms of saturation steps, can only be decided by experienced test subjects. Saturation scales of each of the color systems under review were found by test subjects to be perfectly uniform when they were shown separately for each system. When they were directly compared, no scale was found to be significantly better.[19]

The Coloroid Color System in Education and Design

In Hungary, the Coloroid color system has been applied in primary, secondary, and higher education, as well as in environmental color design. The Coloroid color system has been officially issued by the Hungarian Office for Standardization in 1982.[20] The aesthetic uniformity of the Coloroid color system is especially favorable in design. Relations between Coloroid color symbols express relationships of color harmony. Colors equidistant in Coloroid color planes

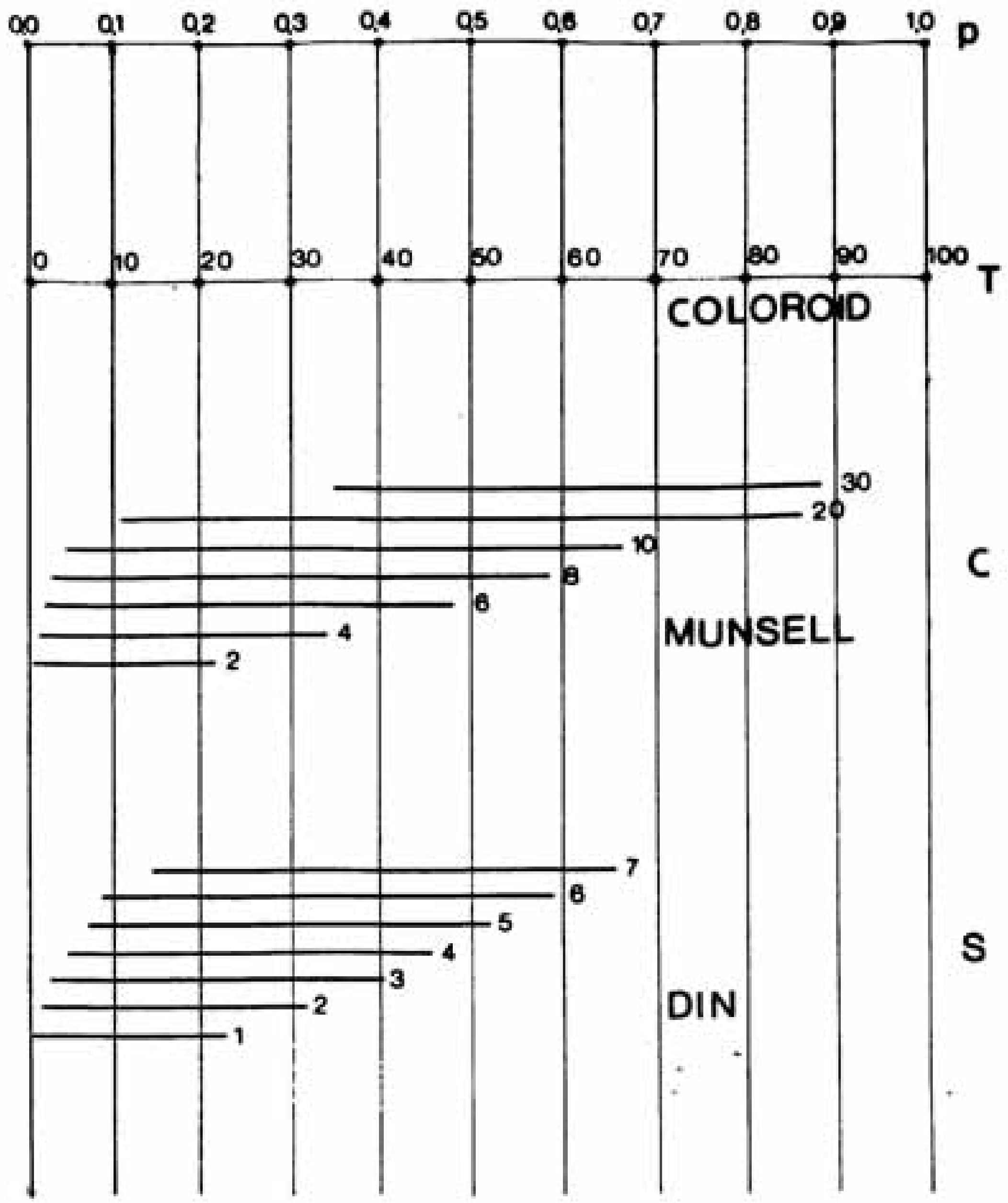

FIG. 6. Color content (excitation purity) *p* for the Coloroid, Munsell, and DIN saturation scales.

are felt to be harmonic (Fig. 7).[21,22] In Fig. 7 the Coloroid color space and the embedded Coloroid surface color solid have been cut by a plane crossing complementary hues *A*44 to *A*71. A mesh of straight lines connecting colors of the same saturation and lightness has been superimposed on the color-solid section. Intersections define mutually harmonizing colors. Colors represented by dots might constitute, e.g., a dynamic composition. Numbers expressing Coloroid saturation and lightness of such colors form an arithmetic progression, such as that illustrated in Table V. The Coloroid color system permits the designer to confine—relying on disclosed and quantified features and demands—the parts of color space that most favorably meet architectural, aesthetic, functional, and lighting demands on the building (see Fig. 8).[23] In Fig. 8 horizontal axes in the diagrams on top represent the Coloroid hue scale *A*, saturation scale *T*, and lightness scale *V*, in this order. The vertical axes indicate preference percentages summed according to various aspects of design. Shaded areas above the curves define ranges of hue *A*, saturation *T*, and lightness *V* to contain planned

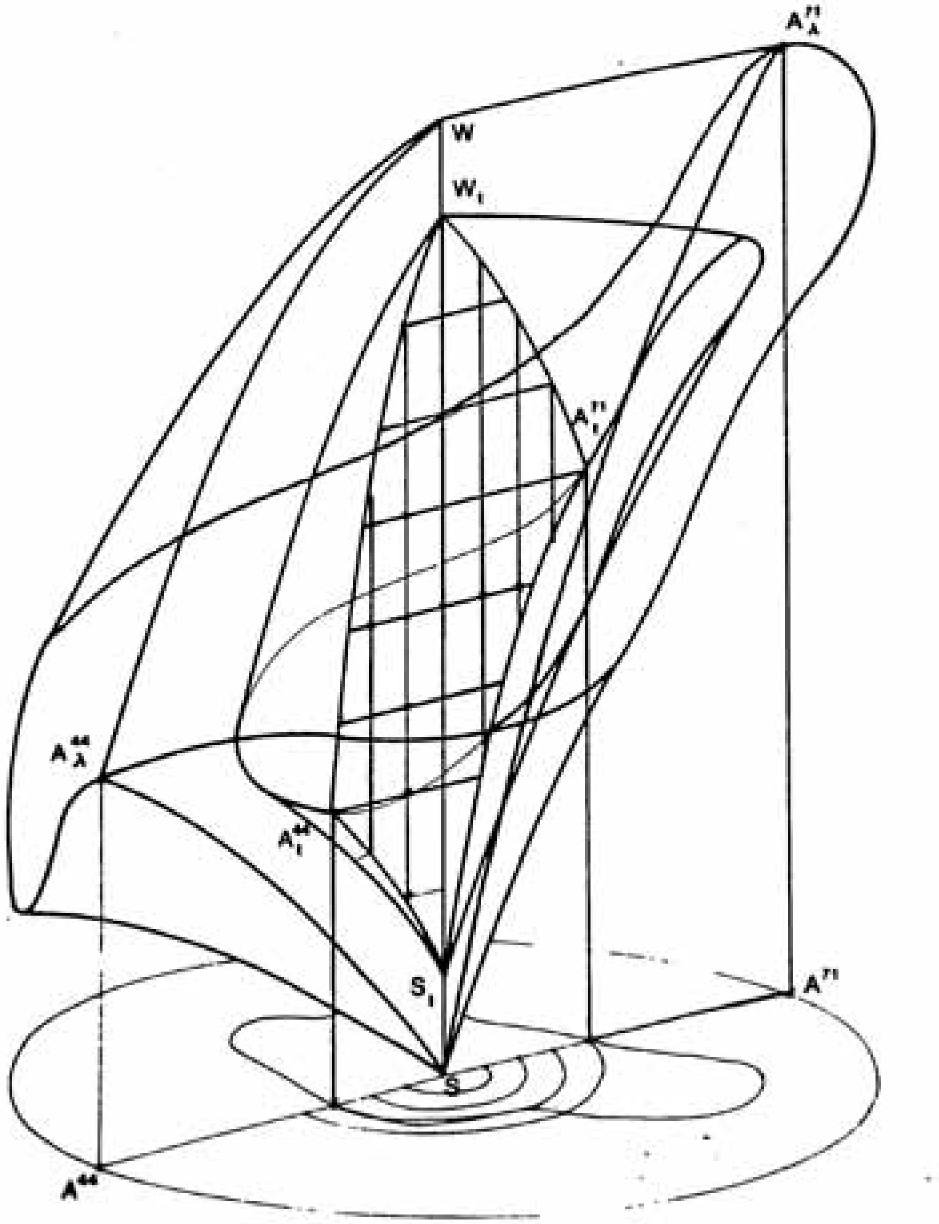

FIG. 7. Geometrical locations of colors composing harmonic color complexes in the Coloroid color solid. See text for explanation.

TABLE III. Coloroid indices of harmonic color series. *A* is the Coloroid hue, *T* the Coloroid saturation, and *V* the Coloroid lightness.

Series 1			Series 2			Series 3		
A	*T*	*V*	*A*	*T*	*V*	*A*	*T*	*V*
44	10	30	44	10	60	44	20	30
44	10	40	00	00	60	44	10	40
44	10	50	71	10	60	00	00	50
44	10	60	71	20	60	71	10	60
44	10	70	71	30	60	71	20	70

colors for architectural construction. These three graphs delimit concrete parts of the Coloroid color solid, as illustrated in the lower portion of the figure. The color designer will choose colors for his design from among colors contained in these distinct regions.

The correlation between the CIE and the Coloroid systems facilitates the realization of any color of the Coloroid color space with simple means, usable also in education. These relationships permit the direct determination, with the help of a specially constructed colorimeter, of both Coloroid

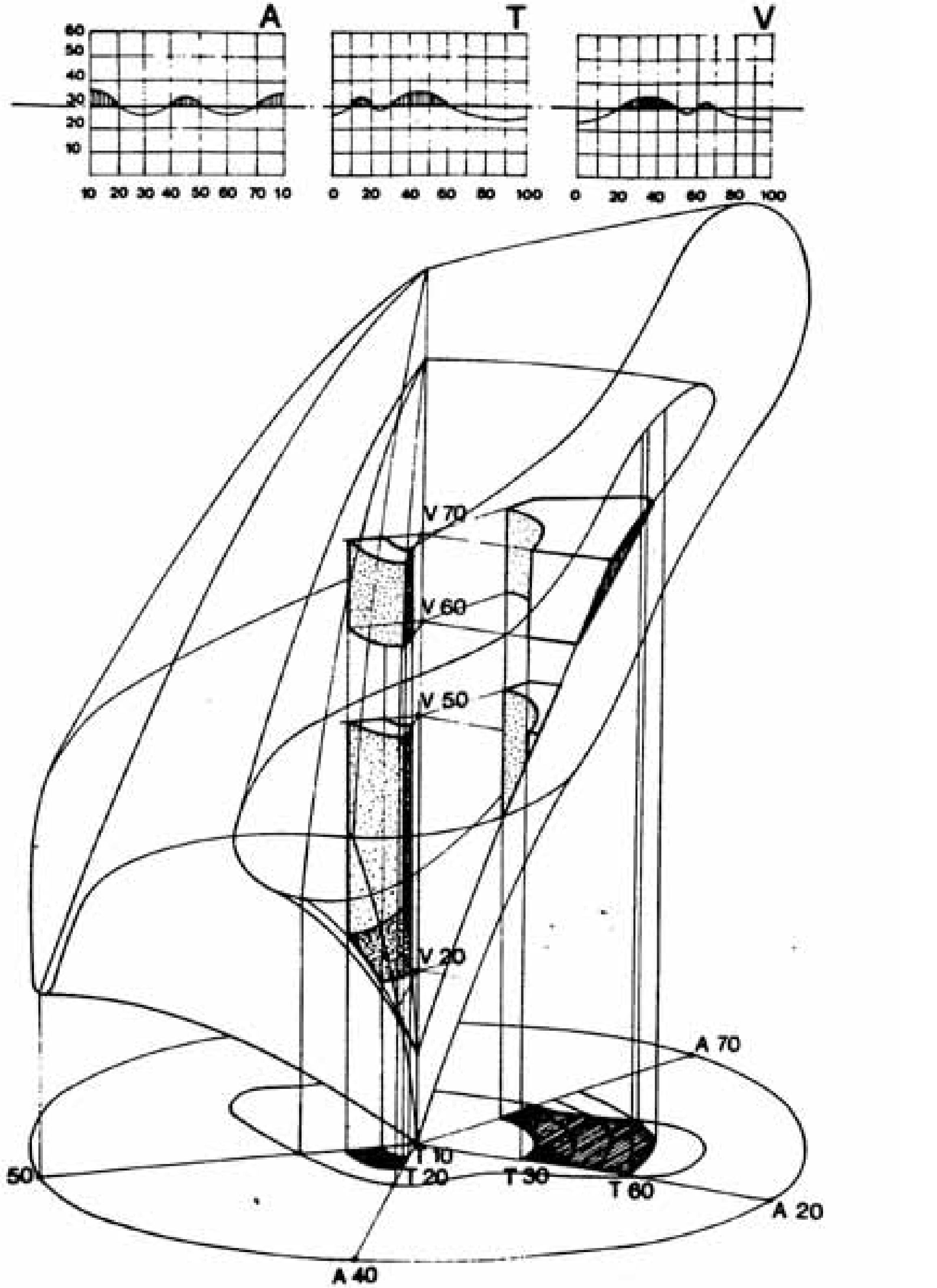

FIG. 8. Color ranges delimited by quantified color design features and demands. See text for explanation.

coordinates and CIE tristimulus values, and the writing of computer programs for converting Coloroid and CIE data.[24]

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